Adaptation of a Miniature Latch Valve into the Aeolus Oxygen Rated In Situ Cleaning System

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ABSTRACT

This paper presents the adaptation of a miniature latch valve for integration into the gaseous oxygen In-situ Cleaning System (ICS) aboard the Aeolus spacecraft which Airbus Defence and Space UK are developing on behalf of ESA. The heritage design was previously qualified as a cold gas micro-thruster for NASA's ST-5 program. Modifications were made to the heritage design to meet the fluid compatibility and higher pressure requirements of the new spacecraft. The development and qualification phases of the miniature latch valve will be presented, focusing on the technical challenges that were faced as well as the aggressive schedule demand that required a unique collaboration between suppliers and end customers alike.

INTRODUCTION

SPACECRAFT OVERVIEW - ESA's Earth Explorer missions are developed in direct response to priorities identified by the scientific community. Carrying novel technologies, each satellite in the series is developed to improve our understanding of how the planet works as a system and the impact that human activity is having on natural Earth processes.

The Atmospheric Dynamics Mission Aeolus (ADM-Aeolus) satellite carries a single instrument – a Doppler wind lidar called ALADIN. This sophisticated instrument is designed to probe the lowermost 30 km of the atmosphere to provide profiles of wind, aerosols and clouds along the satellite's orbital path. Comprised of a powerful laser, a large telescope and a very sensitive receiver, ALADIN is the first wind lidar in space.

Operation of the ALADIN laser requires an ultra-clean environment, supplemented by a constant low pressure pure oxygen gas environment of around 100 Pa. The oxygen environment prevents the build-up of Laser Induced Contamination (LIC) thereby ensuring the continued performance of the payload for the 3.25 year mission lifetime.

Replenishment of the oxygen environment is mandatory to ensure a low level oxygen purge of the ALADIN optics, Airbus Defence and Space (D&S) UK, designed and developed the In situ Cleaning System (ICS). The ICS builds upon over 30 years of heritage for the UK in design, manufacture and test of propulsion subsystems. Instead of providing thrust, the ICS provides a calibrated low flow of pure oxygen to ALADIN using a first of class hybrid regulation cold gas system. The hybrid regulation system uses a mechanical regulator to reduce the oxygen storage tank pressure, which is initially 200 Barg (2900 psig), to an intermediate pressure of 5 Barg (72.5 psig), subsequently operating an electronic "bang-bang" regulation system. The customizable control of the electronic system allows a variety of flow rates to be provided to ALADIN by changing the inlet pressure to a high-precision orifice. Central to the hybrid regulation system are the system's latch valves.

Figure 1: Artistic Depiction of Aeolus Spacecraft Courtesy of ESA [1]

MAROTTA COLD GAS HERITAGE - In the mid 1990s, Marotta Controls Inc. expanded upon its rich history of fluid-control systems and began engineering its first valve designed specifically for managing cold gas aboard satellites. Since then, Marotta's miniature latch valve family has been utilized by a variety of customers, including Airbus D&S, National

Aeronautics and Space Administration (NASA), and Joint Propulsion Laboratories (JPL). Although each valve of the family is unique, they are all based on Marotta's original design: the Cold Gas Micro Thruster (CGMT).

Figure 2: Marotta's Cold Gas Micro Thruster

The CGMT was developed under a contract with NASA for use aboard Space Technology 5 (ST5) as part of the NASA New Millennium program. Tested at 2.7 Newtons of thrust at 138 Bara (2000 psia) and a specific impulse of 65 to 70 seconds, these 60 gram (0.132 lbm) thrusters were used to precisely control the attitude of the formation flying satellites for the duration of its three-month mission in 2006. Designed to perform using the extremely low power (less than 1 watt when powered with the Thrust Control Electronics), the CGMT has proven to be an attractive design that continues to receive attention in the satellite community. Figure 2 shows the CGMT hardware.

MAIN SECTION

AEOLUS LATCH VALVE REQUIREMENTS - The latch valves aboard Aeolus serve two functions for the ICS, firstly providing branch isolation of the prime and redundant feed lines from the high-pressure tanks, and secondly to provide pulsed regulation of the low-pressure feed lines throughout the mission lifetime. See Figure 3 for their placement in the ICS. As with all of the ICS equipment, the valves must be fully oxygen safe. The analysis, certification, and qualification of this compatibility was achieved by invoking specific material requirements to all the equipment subcontractors and subsequently qualifying those equipment for use on Aeolus. The validation approach followed a multi-step process in line with NASA's recommendations for oxygen service.

1. Review the environment in which the equipment is used, including pressure, ambient temperature, fluidic worst-case temperature (due to adiabatic heating), oxygen concentration and system cleanliness for both particulate and non-volatile residue.

2. Consolidate and evaluate the materials used within the equipments for compatibility with the environmental conditions reviewed in step 1. Perform an Oxygen Hazard and Fire Risk Assessment (OHFRA) to determine the level of risk inherent with the equipment design.

Where the level of risk is deemed too high to accept, material changes were made to both metallic and non-metallic components in order to reduce the risk followed by a re-evaluation of the OHFRA.

Marotta's latch valve was selected by Airbus D&S because it was the smallest latch valve available on the market today. It was recognized that a minimal number of changes would need to be implemented in order to achieve the desired oxygen compatibility of the valve.

Specific requirements were necessary to ensure full functionality of the unit with the ICS. A summary of these requirements and design drivers is presented below.

1. The valve must be a bistable design, capable of being opened using a 60ms, 28VDC pulse command. Since the ICS design was retrofitted into the original Aeolus spacecraft, the number of driver circuits available was extremely limited. A monostable solenoid valve was out of the question, hence regulation and branch isolation must be achieved using the same bistable latching valve. The valve must also be low power in order to minimize the additional power drain due to the introduction of the ICS to the satellite.

2. Since the valve is to be used for both branch isolation and also electronic regulation the unit shall be qualified to the highest pressure present within the ICS of 200 Barg (2900 psig).

3. Due to the oxygen safety implications, and moreover to achieve the desired cleanliness level required to prevent contamination of the ALADIN payload, the cleanliness requirements for the valve and other equipment would be in excess of traditional chemical and even electric propulsion cleanliness requirements. The required cleanliness levels were taken from IEST-STD-1246D (formerly MIL-STD-1246C) and set at Particulate Level 25, with an NVR content of less than Level A/2 (< 5 ppm).

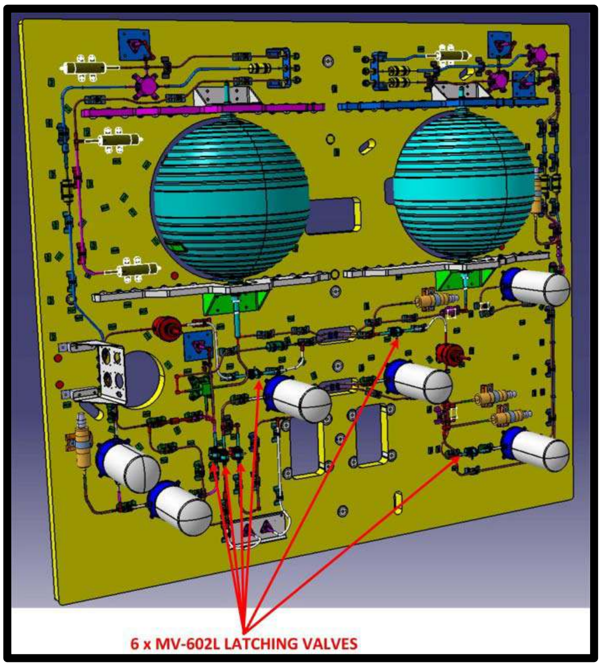


Figure 3: Computer Generated Model of the Aeolus In-Suit Cleaning System [1]

MAROTTA'S MINIATURE LATCH VALVE DESIGN -

CGMT Design - The CGMT is classified as a 2-way, 2-position, plunger-style, magnetically-latching solenoid valve. Figure 4 shows a cutaway view highlighting the key elements of the design. The core of the design is the bimetal, fully-welded pressure vessel (item 3). This welded configuration works both to maintain extremely tight leakage rates as well as to create a unique flux path for the solenoids and magnets that is key to the CGMT's operation. The pressure vessel's inlet is a 6.35 mm (1/4”) diameter weldable stainless steel Stub Tube (item 1) that is threaded and welded into the Inlet Stop (item 2).

For actuation, a pair of Solenoid Coils (item 11) are electrically wired in series and encase the pressurized vessel. Between these Coils resides a set of Samarium Cobalt permanent Magnets (item 12) that are utilized to latch the valve in the open and closed positions when no power is delivered to the Solenoid Coils.

Inside of the pressure vessel resides a small Plunger Assembly (or armature) that is magnetically driven by the Coils. During operation this Plunger Assembly works against the Seat of the valve to create the sealing element of the valve. The Seat is integral to the outlet thruster cone.

CGMT Operation - In the de-energized, latched closed position, the Samarium Cobalt magnets maintain a constant magnetic flux through the Plunger Assembly and the Seat. This magnetic flux generates enough force on the Plunger Assembly (and subsequently, the Poppet) to create a pressure seal against the Seat.

To open the valve, Marotta’s Thruster Controller Electronics (TCE) is used to apply a short square wave voltage pulse across the flying leads with positive voltage applied to the red lead. At this time, the flux generated by the Solenoid Coils work to overpower the magnets' flux and pull the Plunger Assembly away from the Seat and towards the Inlet Stop.

Once de-energized, the magnets maintain a constant flux through the Plunger Assembly and Inlet Stop.

To open the valve, the TCE applies a short square wave voltage pulse across the flying leads with positive voltage applied to the black lead. This switch in polarity drives the magnetic flux in the opposite direction, pulling the plunger towards the Seat. Upon removal of power, the valve will again be in the de-energized, latched closed position.

During qualification for ST5, the CGMT held internal leakage rates to less than 1.0 x 10^{-6} SCCS GHe during random vibration, shock testing, thermal vacuum testing and cycle life testing. Opening and closing response times were less than 3 milliseconds. Operational temperatures were successfully tested in the range of -20ºC to 40ºC.

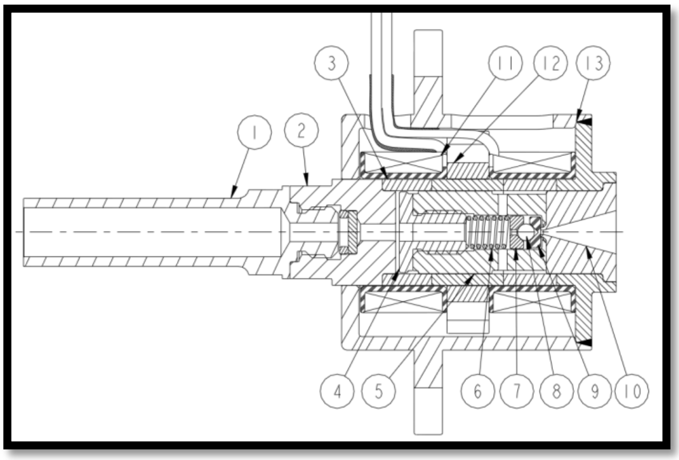


Figure 4: Cutaway of CGMT

Design Modifications - The valve that was designed for the Aeolus spacecrafts' Latching Valve is a part of the MV602L family. Starting with the CGMT, the first design change that took place was to eliminate the thruster cone and replace it with a 6.35 mm (1/4”) diameter stainless steel weldable outlet tube. The inlet tube diameter was also modified to the same diameter per Airbus D&S's request. From there, the pressure vessel of the valve was made more robust in order to meet the required margins of safety at 200 Barg (2900 psig). The pressure vessel’s wall thickness was increased by 15% percent. A finite element analysis yielded a structural safety factor of 3.22.

Due to the increase of the pressure vessel's outer diameter, the solenoid coils needed to be redesigned. In addition, the number of turns on each of the coils was increased to account for the 200 Barg (2900 psig) GOx line fluid. Furthermore, the new coils were designed such that only one coil was needed to open the valve and one to close it. This simplified the customer's electrical interface as it eliminated the need for the Aeolus satellite to reverse the polarity on its electrical interface. The coil's design was completed with a resistance of 178 ohms per coil and an actuation margin of 2.47 (actual force output of solenoid / force required for actuation under worst-case conditions). Figure 5 depicts the magnetic flux of the magnets while in the closed de-energized position.

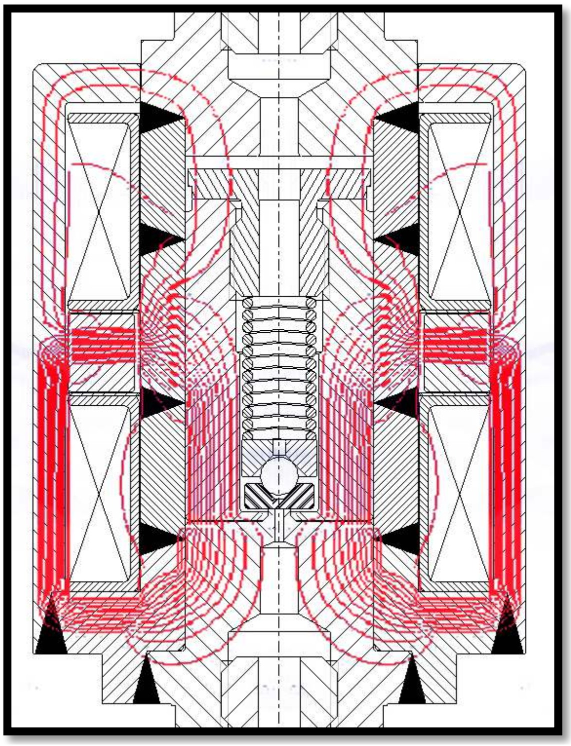
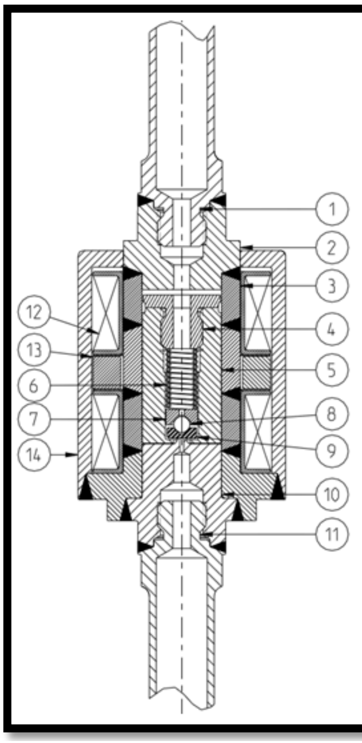


Figure 5: MV602L Flux Path (Valve Shown in Closed Position)

Lastly, to fulfill the oxygen compatibility requirements of Aeolus' ICS, the CGMT's materials were altered. The heritage design was unsuited for high-pressure oxygen service due to dynamic interactions between stainless steel parts (impact ignition). During the opening and closing operations, the Plunger Assembly would be in contact with the Inlet Stop, Seat, and inner diameter of the stainless steel pressure vessel. All of these materials needed to be composed of a magnetic alloy in order to maintain the flux paths for operation. To address this, the MV602L's Plunger Housing and Spring Retainer were coated with 0.0127 mm (0.0005”) of Nickel Plating. Nickel plating is known to be highly resistant to ignition and combustion in high-pressure GOx. The plating of the Plunger Housing and Spring Retainer mitigated both the frictional heating risk as well as the potential of stainless steel particles being dislodged from friction that could cause particle impacts and ignite in the rich oxygen environment.

Since the Plunger Housing and Spring Retainer were both to be nickel plated, they could no longer be welded together as done in the heritage design. The alternative thread locking mechanism that was employed was a small slug of PCTFE that was lodged in a tiny recess perpendicular to the threads of the Spring Retainer. (A slug of the PCTFE material that was used in the valves was tested at NASA White Sands Test Facility in New Mexico USA per ASTM G72/G72M-09, “Standard Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment.” Results of this test yielded an approval for PCTFE’s use in the high-pressure oxygen environment of the Aeolus ICS).

Furthermore, materials inside of the Plunger Assembly were modified to mitigate any potential ignition of stainless steel parts. A previously CRES 302 Spring was converted to Elgiloy (a cobalt alloy). A CRES 316L Ball Retainer became Monel (a nickel-copper alloy). A CRES 440C Ball was made from a ceramic material called silicon nitride. All of these materials are considered non-ignitable at the valve's operational pressures per NASA-RP-1113, Design Guide for High Pressure Oxygen Systems [2] and Marshall Spaceflight Handbook 527 [3].



Item No.	Part Name
1	Inlet
2	Inlet Stop
3	Pressure Vessel
4	Spring Retainer
5	Plunger Housing
6	Spring
7	Ball Retainer
8	Ball
9	Poppet
10	Seat
11	Outlet
12	Coil
13	Magnet
14	Housing

Figure 6: Cutaway and Part Identification of MV602L

Prior to release for qualification testing, the MV602L went through an extensive design review by Airbus D&S & ESA. At the conclusion of the design review, the MV602L's design was concluded to be fully compliant to the design specification and safe for oxygen use.

MV602L'S PERFORMANCE DURING COMPONENT QUALIFICATION - A strict, regimented qualification test plan for the MV602L was laid out in the Aeolus ICS procurement specification. Testing included electrical functionality, mechanical functionality, and environmental testing (shock, vibration, and thermal cycling) to be performed on a single unit. SN113 was used as Marotta's qualification unit. Furthermore, structural margin testing (pressurization to burst) was to be performed on a separate unit. The test matrix of SN113's qualification is provided below in Table 1.

Test Sequence	Test Description
1	Inspection/Examination
2	Proof Pressure
3	Cleanliness Verification
4	Mechanical Functional Checks
5	Electrical Functional Checks
6	Resonance Search
7	Sinusoidal Vibration
8	Resonance Search
9	Rand Vibration
10	Resonance Search
11	Shock Testing
12	Cleanliness Verification
13	Mechanical Functional Checks
14	Electrical Functional Checks
15	Cleanliness Verification
16	Thermal Vacuum
17	Life Test
18	Cleanliness & Dryness Verification
19	Mechanical Functional Checks
20	Electrical Functional Checks
21	Electromagnetic Testing
22	Burst Pressure
23	External Leak (if possible)
24	Inspection/Examination

Table 1: SN113 Qualification Test Matrix

All electrical and mechanical functionality qualification tests were performed at ambient conditions. SN113 successfully passed all qualification tests. Actual response times of the qualification valves were recorded as 10.7 milliseconds to open and 9.7 milliseconds to close. Power draw to open and close the valve were 1.42 watts and 0.96 watts respectively.

Tests were conducted to measure combined internal and external leakage rates as 3.8 x 10^{-8} SCCS GHe at maximum operating pressure and 2.6 x 10^{-8} SCCS GHe at minimum operation pressure (Requirements: Internal leakage less than 1.0 x 10^{-4} SCCS GHe and external leakage less than 1.0 x 10^{-6} SCCS GHe). The maximum flow of the MV602L was recorded as 212,376 SCCM GN2 (7.5 SCFM GN2) (Aeolus flow requirement = >1354 SCCM).

Shock and vibration testing were performed on SN113 to simulate the effects of a launch environment. With the valve pressurized and recording internal leakage, random vibration levels reached 20 gRMS on each of three perpendicular axes individually. Similarly, shock testing was performed on the same three axes while pressurized (25 Hz at 25g, 1500 Hz at 2000g, and 10,000 Hz at 2000g). No out-of-family leakage was observed and no visual damage occurred during testing.

Thermal cycle testing was performed at a vacuum level of 0.0013 pascals. For qualification, eight thermal cycles were performed per Figure 8. Operational temperatures were a maximum of 60°C (140°F) and a minimum of -20°C (-4°F). Non-operational temperatures were also tested for one cycle at a maximum of 60°C (140°F) and a minimum of -40°C (-40°F). The star symbols in the figure represent mechanical and electrical functionality checks that were performed. Maximum leakage that was recorded at maximum and minimum temperatures were 2.6 x 10^{-7} SCCS GHe and 1.4 x 10^{-7} SCCS GHe respectively.

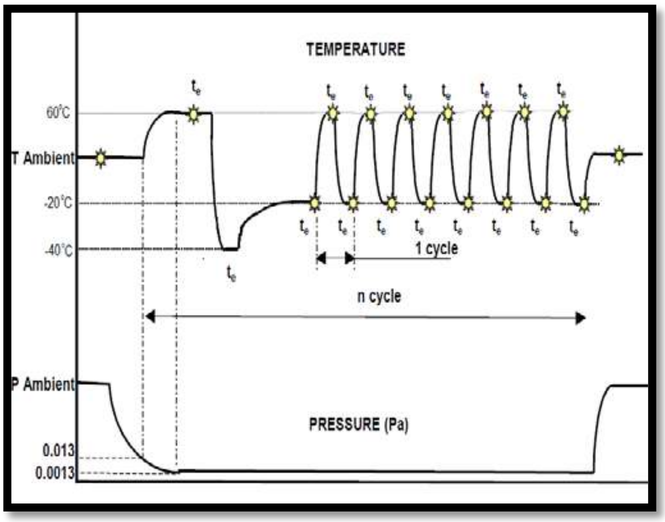


Figure 8: Thermal Cycle Testing Sequence

Post-thermal testing, SN113 was subject to cycle testing. 9750 cycles were performed at 5 Barg (72.5 psig) and 9750 cycles were performed at 200 Barg (2900 psig). Leakage and mechanical tests were conducted after each set of 9750 cycles. The results showed no degradation in performance over all cycles.

Prior to entering qualification testing, SN113 was cleaned to levels in accordance with Level 25 A/2 per IEST-STD-1246D. Throughout the qualification testing, SN113 was subject to periodic cleanliness verification tests to ensure that the valve was not becoming contaminated by the setup nor generating any contamination itself.

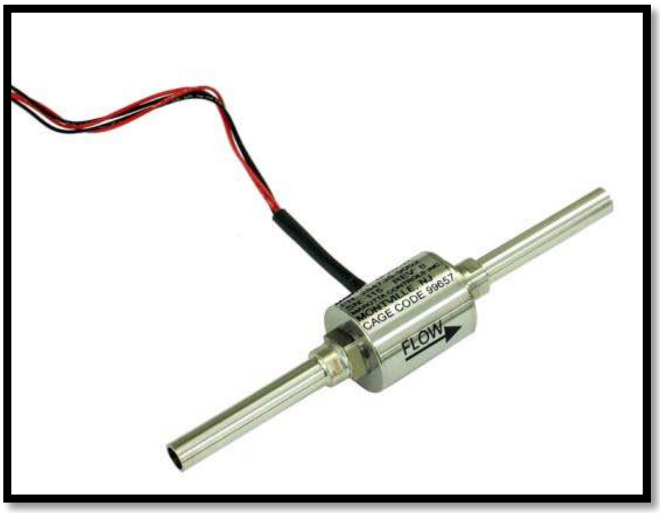


Figure 9: MV602L Flight Hardware

The structural margin testing was performed on a partially assembled MV602L so that any permanent yielding could be accurately measured post-testing. Prior to being subjected to pressure, the outside diameter of the pressure vessel was recorded. The unit was hydraulically pressurized to 2068 barg (30,000 psig) without rupture. Post-pressurization, the pressure vessel's outer diameter was again measured. The results showed a plastic deformation of only 0.051 mm (0.002”) growth in diameter.

CONCLUSION

To meet the requirements for the Aeolus In Situ Cleaning System Latch Valve, Marotta Controls was able to modify a design for a previously flight-qualified Cold Gas Microthruster to adapt to higher pressures, a unique electrical interface, a new mechanical interface, and for use with gaseous oxygen line fluid. Detailed analyses of the design was put forth to satisfy requirements for higher pressure and electrical actuation margin. A rigorous qualification test campaign was successfully executed, providing a new flight qualified design.

In the time since the qualification on the MV602L for use aboard Aeolus, Marotta Controls has also qualified the same design, using SN113 for delta qualification testing, for use in micro cold gas propulsion system of the Lisa Pathfinder spacecraft, also for Airbus D&S. Furthermore, Marotta Controls has internally funded a development program to broaden the use of the MV602L by adding position indication, increasing the maximum flow passage, and design a version for compatibility with hypergolic fluids.

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